Title

Dorsal Horn Parvalbumin Neurons Are Gate-Keepers of Touch-Evoked Pain after Nerve Injury.

Journal

Cell reports, 13(6)

ISSN

2211-1247

Authors

Petitjean, Hugues
Pawlowski, Sophie Anne
Fraine, Steven Li
et al.

Publication Date

2015-11-01

DOI

10.1016/j.celrep.2015.09.080

Peer reviewed

Published in final edited form as:

Cell Rep. 2015 November 10; 13(6): 1246–1257. doi:10.1016/j.celrep.2015.09.080.

Dorsal Horn Parvalbumin Neurons Are Gate-Keepers of Touch-Evoked Pain after Nerve Injury

Hugues Petitjean[1], **Sophie Anne Pawlowski**[3], **Steven Li Fraine**[1], **Behrang Sharif**[1], **Doulia Hamad**[1], **Tarheen Fatima**[1], **Jim Berg**[5,7], **Claire M. Brown**[1,2], **Lily-Yeh Jan**[5], **Alfredo Ribeiro-da-Silva**[3,4], **Joao M. Braz**[6], **Allan I. Basbaum**[6], and **Reza Sharif-Naeini**[1,*]

[1]Department of Physiology and Cell Information Systems Group, McGill University, Montreal, H3G0B1 QC, Canada

[2]Advanced BioImaging Facility, McGill University, H3G0B1 QC, Canada

[3]Department of Pharmacology and Therapeutics, McGill University, H3G1Y6 QC, Canada

[4]Department of Anatomy and Cell Biology, McGill University, H3A0C7 QC, Canada

[5]Departments of Physiology and Biochemistry, Howard Hughes Medical Institute, University of California, San Francisco, 1550 4th Street, RH-490D, San Francisco, CA 94158, USA

[6]Department of Anatomy, University of California, San Francisco, 1550 4th Street, RH-348E, San Francisco, CA 94158, USA

SUMMARY

Neuropathic pain is a chronic debilitating disease that results from nerve damage, persists long after the injury has subsided, and is characterized by spontaneous pain and mechanical hypersensitivity. Although loss of inhibitory tone in the dorsal horn of the spinal cord is a major contributor to neuropathic pain, the molecular and cellular mechanisms underlying this disinhibition are unclear. Here, we combined pharmacogenetic activation and selective ablation approaches in mice to define the contribution of spinal cord parvalbumin (PV)-expressing inhibitory interneurons in naive and neuropathic pain conditions. Ablating PV neurons in naive mice produce neuropathic pain-like mechanical allodynia via disinhibition of PKCγ excitatory interneurons. Conversely, activating PV neurons in nerve-injured mice alleviates mechanical hypersensitivity. These findings indicate that PV interneurons are modality-specific filters that gate mechanical but not thermal inputs to the dorsal horn and that increasing PV inter-neuron activity can ameliorate the mechanical hypersensitivity that develops following nerve injury.

In Brief

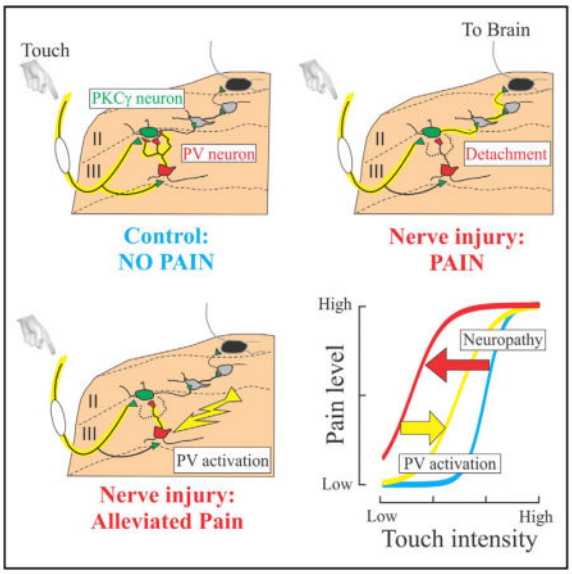
*Correspondence: reza.sharif@mcgill.ca.

[7]Present address: Allen Institute for Brain Science, Seattle, WA 98103, USA

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures and six figures and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2015.09.080.

Improved therapy for neuropathic pain requires a better understanding of the spinal cord neuronal networks that process peripheral sensory inputs in health and disease. Petitjean et al. find that a subset of inhibitory interneurons, containing the marker parvalbumin (PV), prevent touch inputs from activating pain circuits. After nerve injury, a decrease is seen in the number of these synapses, and light touch can elicit pain.



INTRODUCTION

Neuropathic pain is a chronic debilitating disease that follows nerve injury, persists long after the initial injury has subsided, and decreases the quality of life of the patients (Jensen et al., 2007). Despite a plethora of medications and treatment modalities, new treatment approaches for neuropathic pain are needed. Two hallmarks of neuropathic pain are spontaneous pain and mechanical allodynia, a painful response to an innocuous stimulus, such as gentle touch. These symptoms are due in part to a spinal cord dysfunction characterized by decreased inhibitory controls (Castro-Lopes et al., 1993; Moore et al., 2002; Lever et al., 2003; Coull et al., 2003). Enhancing inhibition by activating spinal GABA receptors is effective in some animal models of chronic pain, but the use of GABA agonists in patients is limited due to lack of efficacy and/or adverse side effects (Munro et al., 2009). These shortcomings are due in part to our limited understanding of the neuronal circuitry through which the loss of inhibitory control is manifested (Braz et al., 2014).

Particularly relevant to this question is that touch-sensitive Aβ primary afferent fibers can access spinal cord nociceptive (pain) circuits through polysynaptic pathways (Torsney and MacDermott, 2006). Under normal conditions, these pathways are under tonic inhibition, likely derived from glycinergic inter-neurons located in deeper laminae (Takazawa and MacDermott, 2010). However, in the setting of nerve injury, this inhibitory input is reduced, thereby enabling Aβ fiber-transmitted innocuous inputs to engage and activate nociceptive pathways (Torsney and MacDermott, 2006); see Figure 1. The particular circuits that are

disinhibited and whether the disinhibition involves the death of inhibitory interneurons are not clear (Polgár and Todd, 2008).

Here, we used genetic and functional approaches to examine the contribution of parvalbumin (PV)-expressing inhibitory inter-neurons as gate-keepers of the touch-pain circuitry in the dorsal horn. The location of these interneurons at the border between inner lamina II (IIi) and III is ideal for the modulation of mechanical inputs derived from myelinated primary afferent fibers. However, there is currently nothing known about their contribution to the processing of sensory information in the dorsal horn.

We report that PV interneurons act as modality-specific filters of sensory inputs in the dorsal horn. Increasing their activity significantly alleviates the mechanical allodynia in a mouse model of neuropathic pain. Conversely, selective ablation or silencing of PV interneurons induces mechanical allodynia in naive mice. Using electron microscopy, we identified synaptic contacts between PV^+ terminals and $PKC\gamma^+$ excitatory interneurons. Nerve injury or ablation of PV neurons results in a significant decrease in the number of these contacts, which disinhibits PKCγ interneurons and leads to mechanical allodynia. Inhibition of PKCγ interneurons attenuates mechanical allodynia in both conditions.

RESULTS

Parvalbumin Interneurons Do Not Die after Nerve Injury

It has been suggested that nerve-injury-mediated disinhibition in the dorsal horn is due to the degeneration of GABAergic inhibitory interneurons (Scholz et al., 2005). Although this claim has been challenged (Polgár et al., 2004), we reexamined the question, focusing specifically on the survival of PV interneurons in the spared nerve injury (SNI) model of neuropathic pain (Shields et al., 2003). Because loss of PV immunostaining following nerve injury does not necessarily indicate loss of PV^+ neurons, we examined a marker that is independent of PV expression. To this end, we crossed a transgenic *Parvalbumin::Cre* (*PV::cre*) knockin mouse to a tdTomato (tdTom, red fluorescent protein) reporter mouse. In *PV::cre; tdTom* mice, tdTom is expressed in the cytosol and processes of PV neurons of the adult spinal cord, independently of the expression level of PV.

Given that the expression pattern of certain markers can change during development (Cavanaugh et al., 2011a), we first asked whether tdTom-expressing cells correspond to the PV-immunoreactive (IR) neurons in the adult. Our experiments (Figures 2A–2C) indicate that 83.7% ± 3.0% of the PV-IR neurons are tdTom positive, and all tdTom-positive neurons are positive for PV-IR. Thus, the expression of tdTom recapitulated the endogenous PV expression, and importantly there is no ectopic expression of tdTom in the spinal cord of the *PV::cre; tdTom* mice. Two previous reports indicated that, in the rat dorsal horn, not all PV-IR neurons are inhibitory (Antal et al., 1991; Laing et al., 1994). To address this question, we stained dorsal horn sections of *PV::cre; tdTom* mice with a mixture of GABA and glycine antibodies and demonstrate that 95.4% of tdTom-expressing neurons are GABA and/or glycinergic (Figure 2D). Furthermore, we observed less than 5% colocalization with Lmx1b (Figure 2E) or Tlx3 (four of 79 neurons, n = 2 mice, data not shown), two transcription factors expressed in excitatory interneurons (Szabo et al., 2015; Foster et al.,

2015). We next determined whether PV neurons die after nerve injury. In agreement with previous studies (Huang et al., 2010; Polgár et al., 2013a; Yamamoto et al., 1989), we observed that the dorsal horn of naive mice contains 12.3 ± 3.4 PV neurons on each side of a 25-μm-thick transverse section. Our results indicate, however, that there is no loss of $tdTom^+$ (i.e., PV) neurons between naive, sham, or nerve-injured mice, 3, 5, or 8 weeks post-nerve injury (Figures 2F and 2G). Given that ~16% of PV-immunoreactive neurons were negative for tdTom expression, it is not possible to know what happens to these neurons after SNI. However, staining with an anti-activated caspase 3 antibody failed to show any evidence of apoptosis in dorsal horns of nerve-injured mice 1, 3, and 8 weeks post injury (data not shown). We conclude that there is no significant loss of PV inter-neurons in the SNI model of neuropathic pain.

Pharmacogenetic Activation of PV Interneurons Reveals Their Modality-Specific Filtering of Sensory Inputs

Although Celio and Heizmann described PV interneurons in the dorsal horn over 30 years ago (Celio and Heizmann, 1981), little is known about their contribution to the processing of sensory inputs. Reports monitoring Fos expression found that PV neurons are not activated by peripheral noxious stimuli (Polgár et al., 2013a; Neumann et al., 2008). Furthermore, approximately 50% of the nerve terminals of large diameter fibers (Hughes et al., 2012), presumably of the Aβ type, receive inputs from PV^+ profiles in the spinal cord, which suggests that they may regulate the processing of innocuous inputs. To assess the function of dorsal horn PV interneurons, we modulated their activity using a pharmacogenetic approach (Alexander et al., 2009; Rogan and Roth, 2011; Dong et al., 2010). This approach uses a modified G_q-coupled muscarinic receptor (M3D) that only responds to an exogenous, blood-brain-barrier-permeable, synthetic agonist: clozapine N-oxide (CNO) (Figure S1). CNO activation of cultured dorsal horn neurons infected with M3D induces membrane depolarization (8.3 ± 3 mV) and generates action potentials in PV interneurons (Figure S1D) (Alexander et al., 2009).

To activate PV neurons in vivo, we injected the lumbar spinal cord of *PV::cre; tdTom* mice with an adeno-associated viral (AAV) vector expressing Cre-dependent *M3D* and the reporter mCitrine (*mCit*). Although a subset of peripheral sensory neurons also expresses PV, we did not observe any M3D expression in dorsal root ganglia (DRG) (data not shown). Figure 3A shows that activation of PV neurons significantly increased baseline mechanical withdrawal thresholds compared to saline-injected mice (1.86 ± 0.30 versus 1.27 ± 0.10 g), without affecting thermal withdrawal latencies (Figure 3B). Furthermore, CNO injection had no effect on mechanical withdrawal thresholds in control virus (mCit alone)-injected *PV::cre; tdTom* mice (baseline: 1.35 ± 0.37; 5 mg/kg CNO: 1.16 ± 0.26 g; data not shown). A subset of ventral horn interneurons expresses parvalbumin (Antal et al., 1990). To exclude their potential activation by CNO, we examined mice injected with the highest dose of CNO on the rotarod test. We found no motor impairment in these mice (Figure 3C). Taken together, our results indicate that dorsal horn PV interneurons function as modality-specific filters of somato-sensory information.

PV Neuron Activation Reduces Nerve-Injury-Induced Mechanical Hypersensitivity

There is no evidence for a direct projection of large diameter, Aβ afferents to pain-transmitting projection neurons of lamina I. In a model of neuropathic pain, however, Aβ fiber stimulation evokes polysynaptic excitation of these projection neurons, an effect that can be reproduced by intracisternal administration of the glycine receptor antagonist, strychnine (Miraucourt et al., 2007). These findings suggest that loss of glycinergic inhibitory inputs contributes to the mechanical allodynia following nerve injury. In fact, PV interneurons co-express GABA and glycine (Laing et al., 1994) and are activated by Aβ fibers (Hughes et al., 2012). Nevertheless, the consequence of decreased function of PV interneurons to mechanical allodynia in neuropathic pain models remains unknown. Here, we asked whether increasing the activity of PV interneurons with CNO can attenuate mechanical allodynia in the setting of nerve injury. We performed these studies in mice that received a unilateral injection of the Cre-dependent AAV-*M3D* 21 days prior to nerve injury.

Figures 3D and 3E demonstrates that activation of PV interneurons ipsilateral to the nerve injury significantly and dose-dependently attenuates the mechanical allodynia (0.58 ± 0.08 g in saline-injected versus 1.00 ± 0.12 g in CNO (3 mg/kg)-injected mice). However, CNO had no effect on mechanical allodynia in control virus-injected *PV::cre; tdTom* mice (0.30 ± 0.04 g in saline-injected versus 0.29 ± 0.17 g in CNO 3 mg/kg-injected mice). To determine whether this attenuation is selective for mechanical inputs, we used an inflammatory pain model associated with both mechanical allodynia and thermal hyperalgesia (Bonin and De Koninck, 2014). In this model, activation of PV interneurons selectively attenuated the mechanical allodynia without affecting the thermal hyperalgesia (Figure 3F). We conclude that increasing the activity of PV interneurons selectively attenuates mechanical allodynia without affecting thermal hypersensitivity.

Parvalbumin Interneurons Target Excitatory PKCγ Interneurons

Activity of PKCγ excitatory interneurons is essential to the development of mechanical allodynia after nerve injury (Miraucourt et al., 2007; Malmberg et al., 1997). In normal conditions, these neurons are under tonic, strychnine-sensitive (Miraucourt et al., 2007, 2009), glycinergic (Lu et al., 2013) inhibition, which prevents the induction of mechanical allodynia (Miraucourt et al., 2007). To determine whether PV interneurons are anatomically positioned to modulate the activity of PKCγ interneurons, we examined the presence of appositions between the terminals of PV interneurons, which express tdTom, and the cell bodies of PKCγ-IR interneurons, which predominate in inner lamina II. Consistent with this hypothesis, we recorded a significant number of PV^+ terminals (3.87 ± 0.41 appositions per PKCγ soma, n = 64 neurons from six mice; Figures 4A–4C). Because a subset of large-diameter sensory afferents express PV (Ernfors et al., 1994; Antal et al., 1990), it is possible that they contribute to the tdTom-positive appositions onto PKCγ interneurons instead of or in addition to the dorsal horn PV interneurons. To evaluate this possibility, we performed double immunohistochemical experiments to determine whether the tdTom-positive terminals colocalize with the vesicular glutamate transporter-1 (VGluT1), a marker of large-diameter myelinated sensory neurons (Hughes et al., 2012). We found that only 0.2% ± 0.1% of the VGluT1-positive terminals colocalized with tdTom in the dorsal horn lamina IIi and III, where the PV and PKCγ interneurons are found (Figures S2A and S2B).

Sensory neurons that express PV are mainly proprioceptors, with axons terminating in deeper laminae of the spinal cord, mainly lamina IX (Zampieri et al., 2014). Not surprisingly, when we examined the colocalization of VGluT1$^+$ terminals with tdTom in lamina IX, we observed a significantly larger percentage of co-localization (55.6% ± 15.7%) than in laminae IIi-III. Additionally, we failed to see any colocalized VGluT1$^+$/tdTom$^+$ terminals on the surface of PKCγ interneurons (Figure S2D). We conclude that the tdTom signal detected on PKCγ interneurons does not originate from peripheral sensory neurons.

To investigate the nature of the appositions, including whether they expressed specific synaptic markers, we immunostained dorsal horn sections from *PV::cre; tdTom* mice for PKCγ and (1) VAMP2 or (2) GlyT2, a presynaptic and an inhibitory presynaptic marker, respectively (Figure 5A). We found significant coincident localization of tdTom$^+$ appositions with VAMP2 and GlyT2 (Figure 5B). We confirmed the inhibitory nature of the tdTom apposition by staining for gephyrin, a postsynaptic marker of inhibitory synapses (Majdi et al., 2007). Our data demonstrate that the terminals of PV neurons appose gephyrin clusters on the soma of PKCγ neurons (Figures 5A and 5B). The average number of appositions per PKCγ soma was similar in all three conditions compared to the situation without synaptic marker (Figure 5B), confirming that these are glycinergic appositions.

To determine whether the appositions constitute functional synapses, we performed electron microscopy on the dorsal horn of naive *PV::cre; tdTom* mice, immunostained for tdTomato and PKCγ. In inner lamina II, we observed tdTom-IR dendrites and boutons (Figure 5C). PKCγ-IR dendrites and somata occurred in the same layer. The tdTom-IR boutons established synapses onto PKCγ-IR dendrites (Figure 5C). The boutons contained pleomorphic vesicles, and the synapses were of the symmetric type, suggestive of inhibitory contacts. As shown in the rat (Peirs et al., 2014), PKCγ labeling was located at the plasma membrane and in the cytoplasm of neurons. Our results therefore indicate that the PKCγ subset of excitatory interneurons is a target of the PV interneurons.

Nerve Injury Induces a Detachment of PV Interneuron Processes, which Disinhibits PKCγ Interneurons

We hypothesize that a decrease in the function of PV interneurons can lead to a disinhibition of the PKCγ interneurons. To determine whether this reduction is caused by a detachment of PV nerve terminals from PKCγ somata, we examined the connections between these two interneurons subtypes in naive and nerve-injured mice. Our data demonstrate that the mean number of PV appositions on PKCγ somata is significantly lower in nerve-injured compared to naive mice (Figure 6A). There is a redistribution of the number of appositions on PKCγ somata (Figures 6B and 6C), with the median shifting from 3.28 appositions in naive to 1.84 in nerve-injured mice.

We hypothesized that if this loss of PV interneurons inputs enables PKCγ interneurons to drive mechanical allodynia after nerve injury, then blocking the activity of the PKCγ interneurons should attenuate the allodynia. To test this possibility, we recorded the mechanical thresholds of naive and nerve-injured mice after intrathecal injection of the selective PKCγ inhibitor γV5-3. Figure 6D shows that blockade of PKCγ has no effect in naive mice but significantly attenuates the mechanical allodynia in nerve-injured mice. In

related studies, we monitored stimulus-induced Fos expression in the superficial dorsal horn. In naive mice, gentle brushing of the hindpaw does not induce Fos expression in neurons of laminae I and III. However, the same innocuous stimulus induces Fos expression ipsilateral to a nerve injury; these mice were intrathecally injected with vehicle (TAT; Figures 6E and 6F). In contrast, pre-treatment with γV5-3 significantly reduced the number of activated (Fos-positive) superficial laminae neurons (Figures 6E and 6F). The anti-allodynic effect of PKCγ inhibition appears to be specific to mechanical inputs as testing γV5-3 in an inflammatory pain model associated with mechanical allodynia and thermal hyperalgesia (Bonin and De Koninck, 2014) attenuated only mechanical allodynia (Figure S3).

Selective Ablation of PV Interneurons in Naive Mice Induces Mechanical Allodynia

The loss of PV neuron-mediated inhibition of PKCγ neuron activity is likely one of many events taking place in the dorsal horn following nerve injury. To examine the effects of this disinhibition in isolation from other mechanisms, we ablated PV interneurons in the dorsal horn of healthy, naive mice. We injected an AAV expressing Cre-dependent ribosome inactivating protein saporin (Ng et al., 2010) in the dorsal spinal cord of *PV::cre; tdTom* mice (Figure S4A). Saporin prevents protein synthesis, which leads to cell death (Stirpe et al., 1992). We validated the AAV-*Saporin* vector in vitro by infecting cultured DRG neurons obtained from a *TRPV1::cre; tdTom* mouse and recording neuronal death over time (Figures S4B and S4C). By 16 days post infection, we recorded a significant reduction in the number of tdTom-positive neurons infected with AAV-*Saporin* compared to control (culture media) (22.1 ± 7.2 versus 70.6% ± 22.4% of baseline in saporin and control, respectively; Figure S4B). The reduction was restricted to Cre-expressing neurons as the number of neurons immunostained with the neuronal marker β3-tubulin, and tdTom-negative, did not significantly change after AAV infection (Figure S4C).

When we injected the AAV-*Saporin* into the dorsal horn of *PV::cre; tdTom* mice, we observed a significant decrease in the number of PV interneurons ipsilateral to the injection (ratio ipsi/contra: 0.55 ± 0.08) 21 days post-infection. On the other hand, a GFP-expressing virus had no effect on PV interneurons number (ratio: 0.98 ± 0.08; Figure 7A, right panel). No other visible neuronal loss was observed, as assessed by neuronal staining (215.1 ± 1.1 neurons ipsilateral to the saporin injection compared to 211.2 ± 0.6 neurons contralateral to the saporin injection, Figure 7A). Because proprioceptor neurons also express PV (Zampieri et al., 2014), we also examined the ipsilateral and contralateral L3-L4 DRGs from the AAV-*Saporin*-treated mice. We found no loss of PV-positive DRG neurons after injection of saporin in the dorsal horn (Figures S5A and S5B), indicating that the loss of tdTom-positive neurons was restricted to the dorsal horn. Most importantly, the selective loss of PV interneurons was associated with a gradual development of mechanical allodynia ipsilateral to the injected side (Figure 7B), with no change in the sensitivity to thermal (heat) stimuli (Figure 7C). This modality-specific sensitization was reproduced in *PV::cre; tdTom* mice that had received an intra-spinal injection of a silencing DREADD (hM4D), which couples to inhibitory G proteins (Figure S5C). These results further confirm the modality-specific filtering function of PV interneurons.

Mechanical Allodynia following PV Interneuron Ablation Occurs via a PKCγ-Dependent Mechanism

Our findings indicate that the PKCγ subset of excitatory inter-neurons is a target of PV interneurons. The kinase activity of PKCγ, by enhancing excitatory (Lan et al., 2001; Lin et al., 2006) and reducing inhibitory (Yan and Surmeier, 1997; Deng et al., 2009) transmission, is critical to the development of mechanical allodynia (Malmberg et al., 1997; Li et al., 2005; Shumilla et al., 2005; Miraucourt et al., 2007). We therefore asked whether the mechanical allodynia observed after ablation of PV interneurons resulted from loss of inhibitory control of the PKCγ interneurons. Potentially relevant to this scenario is the result of our immunofluorescence experiments indicating that the percentage of PKCγ neurons without apposition from PV interneurons is significantly increased in the AAV-*Saporin*-injected mice compared to control or AAV-*GFP*-injected mice (Figure 7E). Additionally, the mean number of appositions is significantly reduced after ablation of PV neurons. (Figure 7D).

Taken together, these findings suggest that in comparison to control or AAV-*GFP*-injected mice, a greater number of PKCγ interneurons are disinhibited in the AAV-*Saporin*-injected mice. We hypothesized that the loss of inhibitory control over PKCγ interneuron activity would enable these neurons to transfer innocuous information to nociceptive circuits. Indeed, light brushing of the hindpaw ipsilateral to the site of saporin injection induced Fos expression in the superficial lamina of the dorsal horn. No induction was evoked in the superficial laminae of control or AAV-*GFP*-injected mice (Figure 7F). Finally, we speculated that if the mechanical allodynia observed in the AAV-*Saporin*-injected mice resulted from disinhibition of PKCγ interneurons (Li et al., 2005; Shumilla et al., 2005), then blocking the activity of the PKCγ interneurons should attenuate the allodynia. To test this possibility, we recorded mechanical thresholds 20–30 min after intrathecal injection of γV5-3. Figure 7G illustrates that inhibition of PKCγ activity, in fact, significantly reduced the mechanical allodynia produced in the saporin-injected mice (Figure 7G). In contrast, injection of TAT peptide alone did not attenuate the mechanical allodynia.

DISCUSSION

Sensory inputs from the periphery are processed by a complex network of excitatory and inhibitory interneurons in the dorsal horn prior to transmission to projection neurons and from there to the brain (Figure 1). Our understanding of this processing is incomplete, due in part to the heterogeneity of the interneurons. For example, four non-overlapping subsets of inhibitory inter-neurons have been identified, based on their expression of the markers galanin, neuropeptide Y (NPY), neuronal nitric oxide synthase (nNOS), and PV (Tiong et al., 2011). Immunohistochemical experiments have established that noxious stimuli activate the NPY, nNOS, and galanin, subsets of interneurons, with the latter being also engaged by pruritic stimuli (Kardon et al., 2014). The PV neurons, however, appear not to be activated by noxious (and possibly not by pruritic) stimuli (Polgár et al., 2013a). Our results are the first to characterize the role of PV neurons to the processing of sensory inputs and thus advance our understanding of the organization of inhibitory circuits in the dorsal horn.

Contribution of PV Interneurons to the Processing of Somatosensory Inputs

We used pharmacogenetic tools to control the activity of PV neurons in vivo. Our findings provide the first evidence of a highly selective functional contribution of the PV neurons to the processing of somatosensory information, and critical elements of the circuits that are engaged by these neurons. Activity of the PV neurons prevents innocuous mechanical inputs from activating nociceptive mechanical circuits but has no impact on the transmission of noxious thermal inputs, highlighting their function as modality-specific filters of sensory inputs. Increasing their activity reduces mechanical allodynia in a mouse model of neuropathic pain. The effect of PV neuron activation on mechanical sensitivity is more pronounced in nerve-injured mice compared to naive mice. This may be due to a near-saturation basal activity of PV neurons under control conditions, and a reduced activity after nerve injury. It follows that, in the setting of nerve injury, the net effect of activating PV interneurons with CNO would be more demonstrable. Thus, selectively increasing the activity of PV neurons may be beneficial in the treatment of neuropathic pain.

Postsynaptic Targets of PV Interneurons

In the mouse dorsal horn, PV interneurons have an extensive dendritic arborization in the rostro-caudal axis (Hughes et al., 2012). Consistent with previous reports, we observed that PV axons are largely limited to lamina IIi, occasionally extending into lamina IIo, but they never reach lamina I. Furthermore, we found that PV interneurons form synapses onto PKCγ excitatory interneurons, which populate lamina IIi and are implicated in mechanical allodynia (Malmberg et al., 1997; Miraucourt et al., 2007). The functional relevance of this synaptic connection remained unknown. We showed that selective ablation of PV neurons precipitated a mechanical allodynia comparable to that produced by nerve injury and that was correlated with a significant reduction in the number of appositions onto PKCγ interneurons. The disinhibition of PKCγ interneurons is central to the allodynia, as it was abolished by PKCγ blockade. Taken together, our findings illustrate how a functional interaction between two distinct subsets of dorsal horn interneurons can influence the flow of non-nociceptive information to deeper laminae of the dorsal horn, while concurrently preventing access to pain transmission circuits in the superficial dorsal horn. It was recently reported that a newly identified subset of excitatory interneurons, located mainly in lamina III and expressing the vesicular glutamate transporter VGluT3, contribute to mechanical allodynia (Peirs et al., 2015). These neurons receive low-threshold mechanical inputs, and their activation with pharmacogenetic tools produces mechanical hypersensitivity (Peirs et al., 2015). Whether PV interneurons also target these VGluT3 excitatory interneurons remains to be determined.

Contribution of PV Interneurons to Nerve-Injury-Induced Mechanical Allodynia

Although loss of glycinergic tone is reported to contribute to mechanical allodynia in neuropathic pain models (Lu et al., 2013; Miraucourt et al., 2007; Torsney and MacDermott, 2006; Foster et al., 2015), the mechanisms responsible for the decrease remain unclear. Previous studies reported that inhibitory inter-neurons undergo apoptotic cell death following nerve injury (Scholz et al., 2005). However, we found no change in the number of PV interneurons after nerve injury. On the other hand, the mean number of appositions from

PV nerve terminals onto PKCγ neurons somata is significantly lower after nerve injury. Whether this detachment is enough to explain the mechanical allodynia is not known.

A decrease in excitatory inputs impinging on PV neurons can decrease their inhibitory output. Consistent with this scenario, Lu et al. (2013) showed that the amplitude of the Aβ fiber-evoked excitatory post-synaptic potentials (EPSPs) in glycinergic neurons is significantly smaller in rats with nerve injury than in naive rats. Furthermore, Leitner and colleagues (2013) reported that peripheral nerve injury decreases the frequency of miniature EPSPs in inhibitory interneurons, with no visible change in spine density or morphology (Leitner et al., 2013). Changes in intrinsic membrane properties of PV neurons could decrease their inhibitory function. Parvalbumin neurons are characterized by a high-frequency firing rate and absence of spike frequency adaptation (Hughes et al., 2012, 2013), a process requiring the recruitment of small conductance, calcium-activated potassium (SK) channels (Bischop et al., 2012). By buffering the spike-mediated calcium influx and preventing the calcium from activating SK channels, PV could enable fast spiking (Franconville et al., 2011; Eggermann and Jonas, 2012). In contrast, a decrease in PV expression and a consequent buildup in intracellular calcium would reduce the fast spiking of these interneurons, thus reducing their inhibitory output. Either mechanism would lead to a reduced inhibitory tone on PKCγ interneurons. In fact, Lu et al. demonstrated that peripheral nerve injury significantly reduces the amplitude of glycinergic IPSPs in PKCγ interneurons compared to control rats, with a concomitant increase in transmission failure rate and a decrease in paired-pulse ratio, suggesting a presynaptic mechanism within the glycinergic neurons (Lu et al., 2013).

It was recently reported that dynorphin-expressing GABAergic interneurons, concentrated in lamina I and II, act as a gate to prevent innocuous and noxious inputs from activating somato-statin-expressing excitatory interneurons (Duan et al., 2014), located in lamina II. These inhibitory neurons contribute to the inhibition of itch signals from the periphery (Kardon et al., 2014). They receive mainly polysynaptic Aβ inputs (Duan et al., 2014) as well as inputs from small-diameter afferents, evidenced by their expression of Fos in response to noxious heat, capsaicin, pinch, and formalin (Polgár et al., 2013b). Although the direct synaptic target of these dynorphin-neurons is unknown, they are linked to somatostatin interneurons. Given the morphology of these neurons (Duan et al., 2014) and their dorso-ventral location, they could be downstream targets of PKCγ interneurons.

These putative circuits presumably occur upstream of the mechanism described by De Koninck and colleagues, which also contributes to decreased inhibition following peripheral nerve injury. These authors demonstrated that nerve injury triggers the synthesis and release of brain-derived neurotrophic factor (BDNF) from activated microglia. The latter binds its receptor on lamina I neurons, resulting in a downregulation of the expression of the potassium-chloride co-transporter KCC2. The result of this event is a shift in the chloride gradient of lamina I neurons, which reduces the hyperpolarization effect of inhibitory synapses (Cordero-Erausquin et al., 2005; Coull et al., 2003, 2005; Prescott et al., 2014).

In conclusion, we have identified a subset of inhibitory inter-neurons that normally prevents low threshold mechanoreceptive (tactile) inputs from engaging nociceptive circuits in the

dorsal horn of the spinal cord. In the absence of injury, these PV-containing inhibitory interneurons contact PKCγ-expressing excitatory interneurons and prevent their activation by innocuous tactile stimuli. Importantly, our ablation data indicate that PV interneurons exert a tonic inhibitory control over their targets. By contrast, increasing the activity of PV interneurons alleviated the mechanical allodynia in a mouse model of neuropathic pain. Our results point to the PV interneurons as potential therapeutic targets for the treatment of mechanical allodynia following nerve injury.

EXPERIMENTAL PROCEDURES

Mouse Strains

All mouse strains used have previously been described. *PV::cre*, GFP, and tdTomato reporter mice were obtained from Jackson Labs (stock numbers 008069, 007906, and 007914, respectively*). TRPV1::cre* mice were made by A.I.B. (Cavanaugh et al., 2011b).

Immunohistochemistry

Immunohistochemistry on tissue sections and cell cultures were performed using standard methods (see the Supplemental Experimental Procedures for details).

Behavioral Assays

Experiments were conducted at room temperature. Mice were acclimatized to their testing environment prior to all experiments. Experimenters were blind to the genotype during testing. All experiments were performed on male 8- to 14-week-old mice, according to the Guidelines of the Animal Care Committee of McGill University (see the Supplemental Experimental Procedures for details).

See the Supplemental Experimental Procedures for details on virus injection procedures, detection of appositions, and electron microscopy.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by grants from the Rita Allen Foundation Pain Scholar and the Louise and Alan Edwards Foundation to R.S.-N., from NIH R37NS14627, R01DA29204, and a grant from the Wellcome Trust to A.I.B., R01NS069229 to L.-Y.J. A.R.-d.-S. acknowledges funding from the CIHR (grant MOP-79411). S.A.P. acknowledges a postdoctoral fellowship from the Alan Edwards Center for Research on Pain. Imaging and image analysis was conducted in the Advanced BioImaging Facility.

References

Alexander GM, Rogan SC, Abbas AI, Armbruster BN, Pei Y, Allen JA, Nonneman RJ, Hartmann J, Moy SS, Nicolelis MA, et al. Remote control of neuronal activity in transgenic mice expressing evolved G protein-coupled receptors. Neuron. 2009; 63:27–39. [PubMed: 19607790]

Antal M, Freund TF, Polgár E. Calcium-binding proteins, parvalbumin- and calbindin-D 28k-immunoreactive neurons in the rat spinal cord and dorsal root ganglia: a light and electron microscopic study. J Comp Neurol. 1990; 295:467–484. [PubMed: 2351764]

Antal M, Polgár E, Chalmers J, Minson JB, Llewellyn-Smith I, Heizmann CW, Somogyi P. Different populations of parvalbumin- and calbindin-D28k-immunoreactive neurons contain GABA and accumulate 3H-D-aspartate in the dorsal horn of the rat spinal cord. J Comp Neurol. 1991; 314:114–124. [PubMed: 1797867]

Bischop DP, Orduz D, Lambot L, Schiffmann SN, Gall D. Control of neuronal excitability by calcium binding proteins: a new mathematical model for striatal fast-spiking interneurons. Front Mol Neurosci. 2012; 5:78. [PubMed: 22787441]

Bonin RP, De Koninck Y. A spinal analog of memory reconsolidation enables reversal of hyperalgesia. Nat Neurosci. 2014; 17:1043–1045. [PubMed: 24997764]

Braz J, Solorzano C, Wang X, Basbaum AI. Transmitting pain and itch messages: a contemporary view of the spinal cord circuits that generate gate control. Neuron. 2014; 82:522–536. [PubMed: 24811377]

Castro-Lopes JM, Tavares I, Coimbra A. GABA decreases in the spinal cord dorsal horn after peripheral neurectomy. Brain Res. 1993; 620:287–291. [PubMed: 8369960]

Cavanaugh DJ, Chesler AT, Bráz JM, Shah NM, Julius D, Basbaum AI. Restriction of transient receptor potential vanilloid-1 to the peptidergic subset of primary afferent neurons follows its developmental downregulation in nonpeptidergic neurons. J Neurosci. 2011a; 31:10119–10127. [PubMed: 21752988]

Cavanaugh DJ, Chesler AT, Jackson AC, Sigal YM, Yamanaka H, Grant R, O'Donnell D, Nicoll RA, Shah NM, Julius D, Basbaum AI. Trpv1 reporter mice reveal highly restricted brain distribution and functional expression in arteriolar smooth muscle cells. J Neurosci. 2011b; 31:5067–5077. [PubMed: 21451044]

Celio MR, Heizmann CW. Calcium-binding protein parvalbumin as a neuronal marker. Nature. 1981; 293:300–302. [PubMed: 7278987]

Cordero-Erausquin M, Coull JA, Boudreau D, Rolland M, De Koninck Y. Differential maturation of GABA action and anion reversal potential in spinal lamina I neurons: impact of chloride extrusion capacity. J Neurosci. 2005; 25:9613–9623. [PubMed: 16237166]

Coull JA, Boudreau D, Bachand K, Prescott SA, Nault F, Sík A, De Koninck P, De Koninck Y. Trans-synaptic shift in anion gradient in spinal lamina I neurons as a mechanism of neuropathic pain. Nature. 2003; 424:938–942. [PubMed: 12931188]

Coull JA, Beggs S, Boudreau D, Boivin D, Tsuda M, Inoue K, Gravel C, Salter MW, De Koninck Y. BDNF from microglia causes the shift in neuronal anion gradient underlying neuropathic pain. Nature. 2005; 438:1017–1021. [PubMed: 16355225]

Deng P, Pang ZP, Lei Z, Xu ZC. Excitatory roles of protein kinase C in striatal cholinergic interneurons. J Neurophysiol. 2009; 102:2453–2461. [PubMed: 19657079]

Dong S, Rogan SC, Roth BL. Directed molecular evolution of DREADDs: a generic approach to creating next-generation RASSLs. Nat Protoc. 2010; 5:561–573. [PubMed: 20203671]

Duan B, Cheng L, Bourane S, Britz O, Padilla C, Garcia-Campmany L, Krashes M, Knowlton W, Velasquez T, Ren X, et al. Identification of spinal circuits transmitting and gating mechanical pain. Cell. 2014; 159:1417–1432. [PubMed: 25467445]

Eggermann E, Jonas P. How the 'slow' Ca(2+) buffer parvalbu-min affects transmitter release in nanodomain-coupling regimes. Nat Neurosci. 2012; 15:20–22.

Ernfors P, Lee KF, Kucera J, Jaenisch R. Lack of neurotro-phin-3 leads to deficiencies in the peripheral nervous system and loss of limb proprioceptive afferents. Cell. 1994; 77:503–512. [PubMed: 7514502]

Foster E, Wildner H, Tudeau L, Haueter S, Ralvenius WT, Jegen M, Johannssen H, Hösli L, Haenraets K, Ghanem A, et al. Targeted ablation, silencing, and activation establish glycinergic dorsal horn neurons as key components of a spinal gate for pain and itch. Neuron. 2015; 85:1289–1304. [PubMed: 25789756]

Franconville R, Revet G, Astorga G, Schwaller B, Llano I. Somatic calcium level reports integrated spiking activity of cerebellar interneurons in vitro and in vivo. J Neurophysiol. 2011; 106:1793–1805. [PubMed: 21734102]

Huang J, Chen J, Wang W, Wang W, Koshimizu Y, Wei YY, Kaneko T, Li YQ, Wu SX. Neurochemical properties of enkephalinergic neurons in lumbar spinal dorsal horn revealed by preproenkephalin-

green fluorescent protein transgenic mice. J Neurochem. 2010; 113:1555–1564. [PubMed: 20367750]

Hughes DI, Sikander S, Kinnon CM, Boyle KA, Watanabe M, Callister RJ, Graham BA. Morphological, neurochemical and electro-physiological features of parvalbumin-expressing cells: a likely source of axo-axonic inputs in the mouse spinal dorsal horn. J Physiol. 2012; 590:3927–3951. [PubMed: 22674718]

Hughes DI, Boyle KA, Kinnon CM, Bilsland C, Quayle JA, Callister RJ, Graham BA. HCN4 subunit expression in fast-spiking inter-neurons of the rat spinal cord and hippocampus. Neuroscience. 2013; 237:7–18. [PubMed: 23357121]

Jensen MP, Chodroff MJ, Dworkin RH. The impact of neuropathic pain on health-related quality of life: review and implications. Neurology. 2007; 68:1178–1182. [PubMed: 17420400]

Kardon AP, Polgár E, Hachisuka J, Snyder LM, Cameron D, Savage S, Cai X, Karnup S, Fan CR, Hemenway GM, et al. Dynorphin acts as a neuromodulator to inhibit itch in the dorsal horn of the spinal cord. Neuron. 2014; 82:573–586. [PubMed: 24726382]

Laing I, Todd AJ, Heizmann CW, Schmidt HH. Subpopulations of GABAergic neurons in laminae I–III of rat spinal dorsal horn defined by coexistence with classical transmitters, peptides, nitric oxide synthase or parvalbumin. Neuroscience. 1994; 61:123–132. [PubMed: 7526265]

Lan JY, Skeberdis VA, Jover T, Grooms SY, Lin Y, Araneda RC, Zheng X, Bennett MV, Zukin RS. Protein kinase C modulates NMDA receptor trafficking and gating. Nat Neurosci. 2001; 4:382–390. [PubMed: 11276228]

Leitner J, Westerholz S, Heinke B, Forsthuber L, Wunderbaldinger G, Jäger T, Gruber-Schoffnegger D, Braun K, Sandkühler J. Impaired excitatory drive to spinal GABAergic neurons of neuropathic mice. PLoS ONE. 2013; 8:e73370. [PubMed: 24009748]

Lever I, Cunningham J, Grist J, Yip PK, Malcangio M. Release of BDNF and GABA in the dorsal horn of neuropathic rats. Eur J Neurosci. 2003; 18:1169–1174. [PubMed: 12956715]

Li HF, Mochly-Rosen D, Kendig JJ. Protein kinase Cgamma mediates ethanol withdrawal hyper-responsiveness of NMDA receptor currents in spinal cord motor neurons. Br J Pharmacol. 2005; 144:301–307. [PubMed: 15655532]

Lin Y, Jover-Mengual T, Wong J, Bennett MV, Zukin RS. PSD-95 and PKC converge in regulating NMDA receptor trafficking and gating. Proc Natl Acad Sci USA. 2006; 103:19902–19907. [PubMed: 17179037]

Lu Y, Dong H, Gao Y, Gong Y, Ren Y, Gu N, Zhou S, Xia N, Sun YY, Ji RR, Xiong L. A feed-forward spinal cord glycinergic neural circuit gates mechanical allodynia. J Clin Invest. 2013; 123:4050–4062. [PubMed: 23979158]

Majdi M, Ribeiro-da-Silva A, Cuello AC. Cognitive impairment and transmitter-specific pre- and postsynaptic changes in the rat cerebral cortex during ageing. Eur J Neurosci. 2007; 26:3583–3596. [PubMed: 18088281]

Malmberg AB, Chen C, Tonegawa S, Basbaum AI. Preserved acute pain and reduced neuropathic pain in mice lacking PKCgamma. Science. 1997; 278:279–283. [PubMed: 9323205]

Miraucourt LS, Dallel R, Voisin DL. Glycine inhibitory dysfunction turns touch into pain through PKCgamma interneurons. PLoS ONE. 2007; 2:e1116. [PubMed: 17987109]

Miraucourt LS, Moisset X, Dallel R, Voisin DL. Glycine inhibitory dysfunction induces a selectively dynamic, morphine-resistant, and neurokinin 1 receptor- independent mechanical allodynia. J Neurosci. 2009; 29:2519–2527. [PubMed: 19244526]

Moore KA, Kohno T, Karchewski LA, Scholz J, Baba H, Woolf CJ. Partial peripheral nerve injury promotes a selective loss of GABAergic inhibition in the superficial dorsal horn of the spinal cord. J Neurosci. 2002; 22:6724–6731. [PubMed: 12151551]

Munro G, Ahring PK, Mirza NR. Developing analgesics by enhancing spinal inhibition after injury: GABAA receptor subtypes as novel targets. Trends Pharmacol Sci. 2009; 30:453–459. [PubMed: 19729210]

Neumann S, Braz JM, Skinner K, Llewellyn-Smith IJ, Basbaum AI. Innocuous, not noxious, input activates PKCgamma interneurons of the spinal dorsal horn via myelinated afferent fibers. J Neurosci. 2008; 28:7936–7944. [PubMed: 18685019]

Ng TB, Wong JH, Wang H. Recent progress in research on ribosome inactivating proteins. Curr Protein Pept Sci. 2010; 11:37–53. [PubMed: 20201806]

Peirs C, Patil S, Bouali-Benazzouz R, Artola A, Landry M, Dallel R. Protein kinase C gamma interneurons in the rat medullary dorsal horn: distribution and synaptic inputs to these neurons, and subcellular localization of the enzyme. J Comp Neurol. 2014; 522:393–413. [PubMed: 23818225]

Peirs C, Williams SP, Zhao X, Walsh CE, Gedeon JY, Cagle NE, Goldring AC, Hioki H, Liu Z, Marell PS, Seal RP. Dorsal Horn Circuits for Persistent Mechanical Pain. Neuron. 2015; 87:797–812. [PubMed: 26291162]

Polgár E, Todd AJ. Tactile allodynia can occur in the spared nerve injury model in the rat without selective loss of GABA or GABA(A) receptors from synapses in laminae I–II of the ipsilateral spinal dorsal horn. Neuroscience. 2008; 156:193–202. [PubMed: 18675320]

Polgár E, Gray S, Riddell JS, Todd AJ. Lack of evidence for significant neuronal loss in laminae I–III of the spinal dorsal horn of the rat in the chronic constriction injury model. Pain. 2004; 111:144–150. [PubMed: 15327818]

Polgár E, Sardella TC, Tiong SY, Locke S, Watanabe M, Todd AJ. Functional differences between neurochemically defined populations of inhibitory interneurons in the rat spinal dorsal horn. Pain. 2013a; 154:2606–2615. [PubMed: 23707280]

Polgár E, Sardella TC, Tiong SY, Locke S, Watanabe M, Todd AJ. Functional differences between neurochemically defined populations of inhibitory interneurons in the rat spinal dorsal horn. Pain. 2013b; 154:2606–2615. [PubMed: 23707280]

Prescott SA, Ma Q, De Koninck Y. Normal and abnormal coding of somatosensory stimuli causing pain. Nat Neurosci. 2014; 17:183–191. [PubMed: 24473266]

Rogan SC, Roth BL. Remote control of neuronal signaling. Pharmacol Rev. 2011; 63:291–315. [PubMed: 21415127]

Scholz J, Broom DC, Youn DH, Mills CD, Kohno T, Suter MR, Moore KA, Decosterd I, Coggeshall RE, Woolf CJ. Blocking caspase activity prevents transsynaptic neuronal apoptosis and the loss of inhibition in lamina II of the dorsal horn after peripheral nerve injury. J Neurosci. 2005; 25:7317–7323. [PubMed: 16093381]

Shields SD, Eckert WA 3rd, Basbaum AI. Spared nerve injury model of neuropathic pain in the mouse: a behavioral and anatomic analysis. J Pain. 2003; 4:465–470. [PubMed: 14622667]

Shumilla JA, Liron T, Mochly-Rosen D, Kendig JJ, Sweitzer SM. Ethanol withdrawal-associated allodynia and hyperalgesia: age-dependent regulation by protein kinase C epsilon and gamma isoenzymes. J Pain. 2005; 6:535–549. [PubMed: 16084468]

Stirpe F, Barbieri L, Battelli MG, Soria M, Lappi DA. Ribosome-inactivating proteins from plants: present status and future prospects. Biotechnology (N Y). 1992; 10:405–412. [PubMed: 1368484]

Szabo NE, da Silva RV, Sotocinal SG, Zeilhofer HU, Mogil JS, Kania A. Hoxb8 intersection defines a role for Lmx1b in excitatory dorsal horn neuron development, spinofugal connectivity, and nociception. J Neurosci. 2015; 35:5233–5246. [PubMed: 25834049]

Takazawa T, MacDermott AB. Glycinergic and GABAergic tonic inhibition fine tune inhibitory control in regionally distinct subpopulations of dorsal horn neurons. J Physiol. 2010; 588:2571–2587. [PubMed: 20498232]

Tiong SY, Polgár E, van Kralingen JC, Watanabe M, Todd AJ. Galanin-immunoreactivity identifies a distinct population of inhibitory interneurons in laminae I–III of the rat spinal cord. Mol Pain. 2011; 7:36. [PubMed: 21569622]

Torsney C, MacDermott AB. Disinhibition opens the gate to pathological pain signaling in superficial neurokinin 1 receptor-expressing neurons in rat spinal cord. J Neurosci. 2006; 26:1833–1843. [PubMed: 16467532]

Yamamoto T, Carr PA, Baimbridge KG, Nagy JI. Parvalbumin- and calbindin D28k-immunoreactive neurons in the superficial layers of the spinal cord dorsal horn of rat. Brain Res Bull. 1989; 23:493–508. [PubMed: 2611692]

Yan Z, Surmeier DJ. D5 dopamine receptors enhance Zn2+-sensitive GABA(A) currents in striatal cholinergic interneurons through a PKA/PP1 cascade. Neuron. 1997; 19:1115–1126. [PubMed: 9390524]

Zampieri N, Jessell TM, Murray AJ. Mapping sensory circuits by anterograde transsynaptic transfer of recombinant rabies virus. Neuron. 2014; 81:766–778. [PubMed: 24486087]

Highlights

- Parvalbumin (PV) neurons of the dorsal horn synapse onto PKCγ excitatory neurons
- After nerve injury, many PV-PKCγ synapses are lost and touch stimuli become painful
- Specific activation of PV neurons after nerve injury alleviates mechanical pain

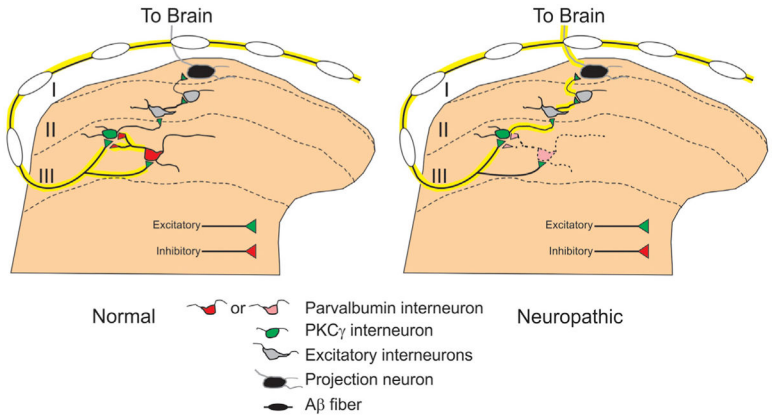


Figure 1. Spinal Lamina I Output Neurons Do Not Receive Direct Input from Low-Threshold Aβ Primary Afferents

Yet a polysynaptic pathway links myelinated Aβ fibers to lamina I neurons (Torsney and MacDermott, 2006). Under normal conditions (left panel), the link is repressed by inhibitory glycinergic interneurons (red, left panel). After nerve injury (right panel), impaired inhibition unmasks the connection, thus enabling low-threshold inputs to drive lamina I projection neurons. Yellow highlighting indicates flow of information. Adapted from Prescott et al. (2014).

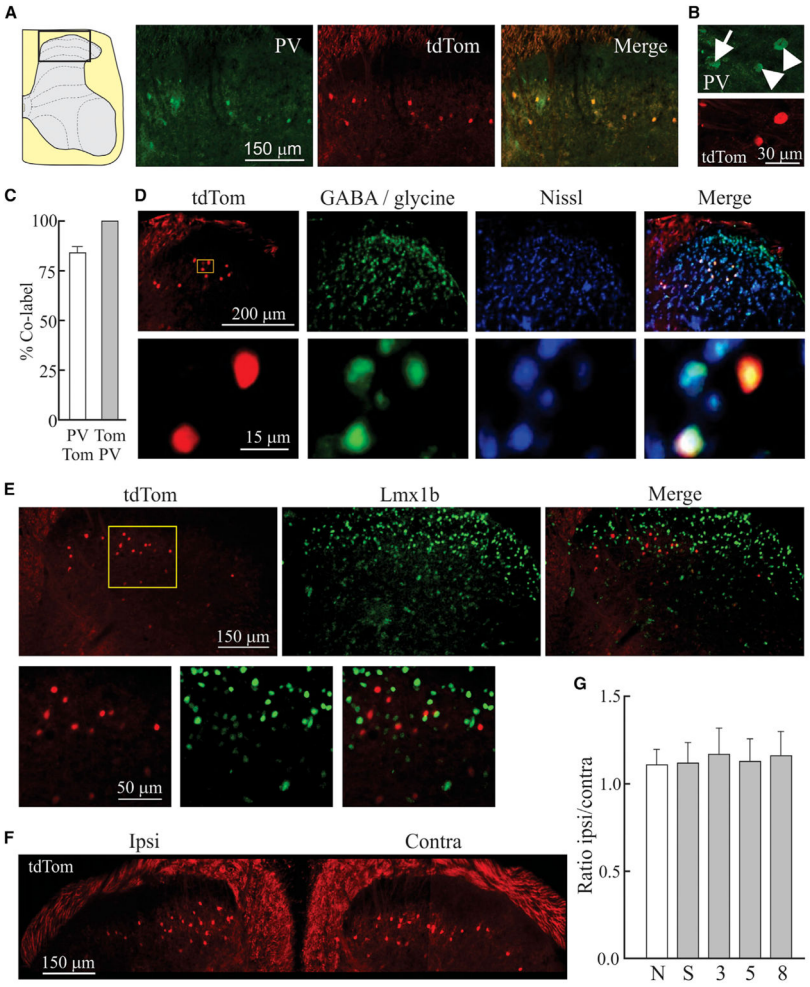


Figure 2. *PV::cre; tdTomato* Transgenic Mice Recapitulate Endogenous PV Expression

(A) Transgenic *PV::cre; tdTomato* mice express tdTom (red) exclusively in PV (green)-expressing interneurons. Scale bar, 150 µm.

(B and C) The vast majority of PV-immunoreactive (IR) neurons (~84%; 142 out 168 neurons, n = 3) express tdTom, and all $tdTom^+$ neurons (142/142) express PV. Scale bar, 30 µm.

(D) Top panels: transverse section of the dorsal horn stained with GABA and glycine antibodies (green) and Nissl (blue). Bottom panels: magnification of top panels. The majority of TdTom-positive PV neurons (~95%; 419 of 439 neurons, n = 5 mice) express GABA and/or glycine.

(E) Top panels: transverse section of the dorsal horn stained with an Lmx1b antibody (green). Bottom panels: magnification of top panels. The majority of PV neurons are Lmx1b negative (62 of 65 neurons, n = 2 mice).

(F) Composite image showing the presence of PV neurons 8 weeks after SNI. Scale bar, 150 µm.

(G) Number of PV interneurons (ratio of ipsi/contra) at different time points after nerve injury. N, naive (n = 5); S, sham-operated (n = 5); 3, 5, and 8, the number of weeks post nerve injury, with n = 5, 7, and 8, respectively.

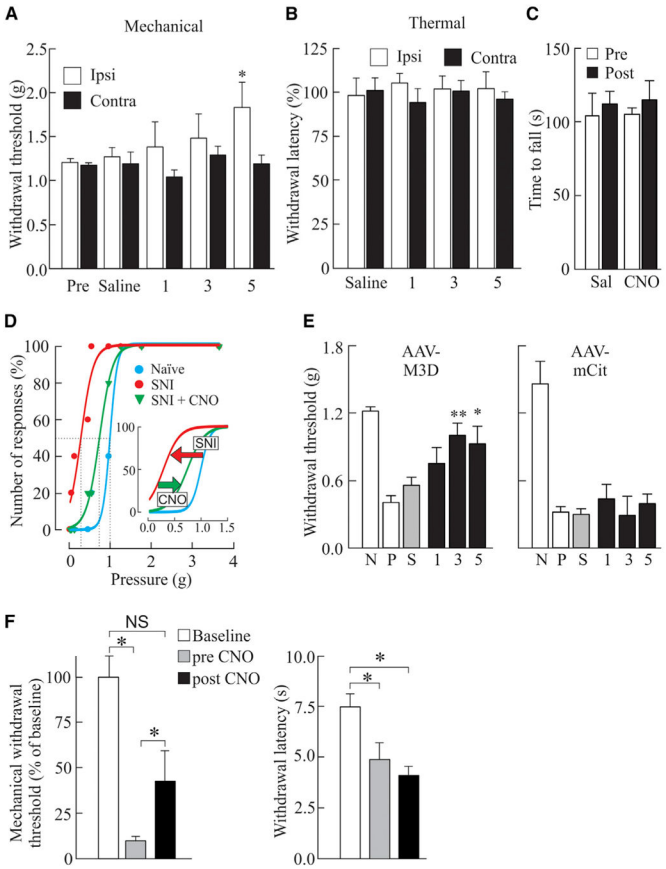


Figure 3. Activation of PV Interneurons Elevates Mechanical Thresholds without Affecting Thermal Sensitivity in Awake Naive and Neuropathic Mice

(A) Activation of PV neurons in naive mice (CNO 5 mg/kg; i.p) significantly increases mechanical withdrawal thresholds (n = 12) ipsilateral to the AAV-M3D injection side. Lower doses of CNO had no effect. *Significant difference from the saline-injected group.

(B) Activation of PV neurons has no effect on thermal withdrawal latency (n = 12).

(C) CNO-injected mice perform as well as saline-injected mice in the rotarod test (n = 3), indicating that 5 mg/kg CNO does not cause any motor impairment.

(D) Peripheral nerve injury (SNI) causes a leftward shift in the behavioral responses to mechanical stimulation (from blue to red curve), indicating mechanical allodynia (see inset). Activation of PV neurons (CNO 3 mg/kg) 20 min prior to testing attenuates the allodynia (green arrow in inset).

(E) Injection of CNO in nerve-injured *PV::cre; tdTomato* mice infected with AAV-M3D significantly attenuates the mechanical allodynia (left panel). No anti-allodynic effects were observed with a control AAV (*mCit* alone). Mechanical thresholds were recorded before and after systemic administration of CNO. N, naive; p, nerve-injured mice, baseline; S, saline injected, nerve-injured mice; 1, 3, and 5, doses of CNO in mg/kg (n = 8–10 mice per group). *,**Significant difference from the saline-injected group.

(F) Activation of PV interneurons modulates mechanical thresholds without affecting thermal sensitivity in an inflammatory pain model. Subcutaneous injection of capsaicin into the heel of the hindpaw induces a significant reduction of mechanical threshold (left panel)

(9.4% ± 2.3%, n = 4, gray bar) that is attenuated following administration of CNO (5 mg/kg; i.p.) in *AAV-M3D*-injected *PV::cre;* mice (42.2% ± 16.7%, n = 4, black bar) ipsilateral to the AAV injection side. The capsaicin injection also produces a significant reduction of thermal withdrawal thresholds (right panel) (4.86 ± 0.71 sec, n = 4, gray bar) compared to baseline values (7.41 ± 0.61 sec, n = 4, white bar). CNO administration had no effect on thermal withdrawal thresholds, demonstrating the modality-specific PV interneuron-mediated inhibition in this model (4.09 ± 0.39 sec, n = 4, gray bar). *Significant difference between groups compared, following a Kruskal-Wallis ANOVA on ranks with multiple comparisons (Student-Newman-Keuls Method). NS, non-significant; i.p., intraperitoneal.

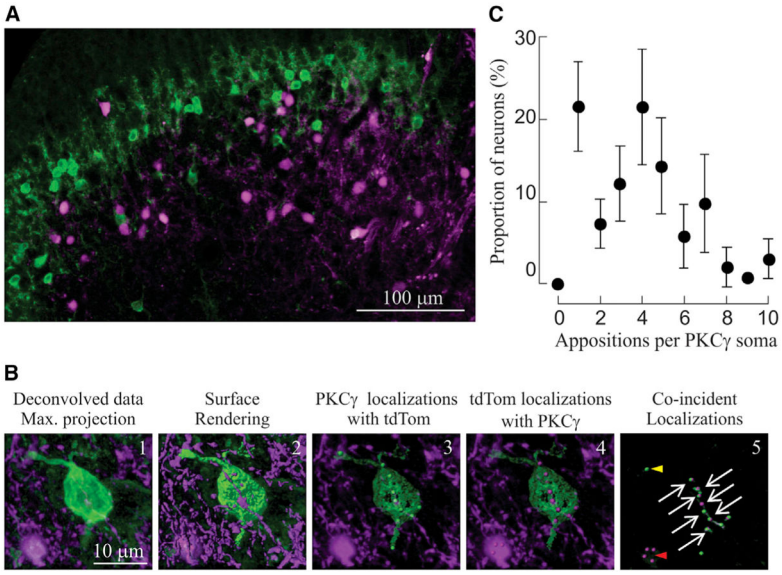


Figure 4. Appositions between PV$^+$ Terminals and Lamina IIi PKCγ-Expressing Inter-neurons

(A) tdTom$^+$ interneurons (magenta) are located in the vicinity of excitatory PKCγ (green) interneurons.

(B) Panels: (1) Maximal projection of a decon-volved z stack of confocal images taken at the 0.1-µm interval and then processed through the Imaris software to define surface rendering (2) of the tdTom profiles surrounding the PKCγ soma. (3) Areas of tdTom signals on the PKCγ surface and of PKCγ signal on tdTom surface (4). The “spot co-localization” feature identifies areas positive for both PKCγ and tdTom. This process defines the number of appositions of tdTom terminals on PKCγ soma, as co-incident localizations (white arrows), and excludes unspecific detections, as PKCγ spots distant from tdTom processes (yellow arrowhead) or tdTom spots distant from the PKCγ soma (red arrowhead). Scale bar, 10 µm.

(C) Mean (±SEM) proportion (%) of PKCγ somata in relation to the number of PV appositions (n = 64 somata from six mice).

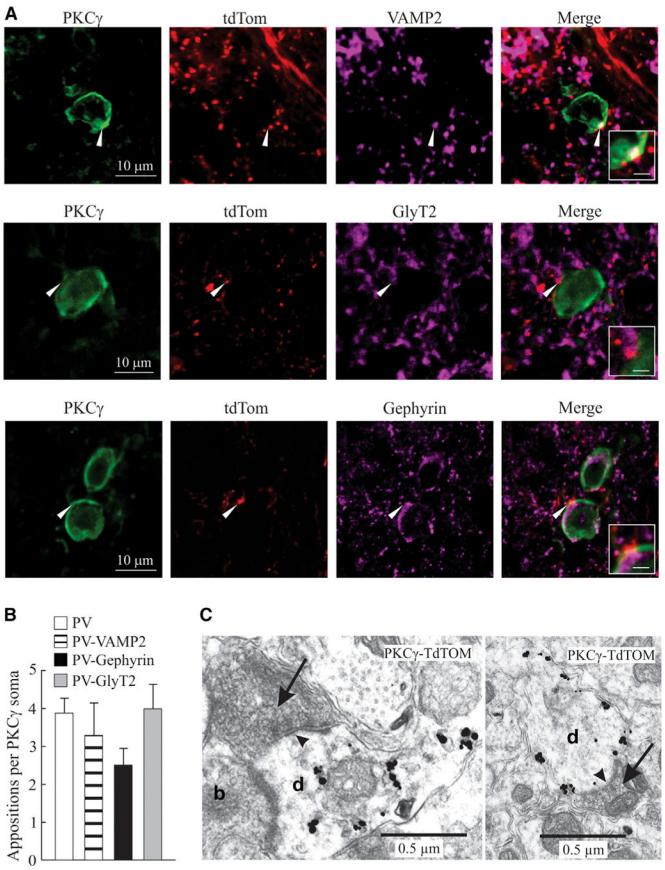


Figure 5. Inhibitory Nature of the Synaptic Connection between PV and PKCγ Inter-neurons

(A) Confocal picture from the lamina IIi of the dorsal horn displaying PKCγ neurons (green), PV neurons' processes (red), and in magenta: VAMP2 (top panel), GlyT2 (middle panel), or gephyrin (bottom panel). Arrowheads in top and middle panel, colocalization of the tdTom and VAMP2 or GlyT2 signals. Bottom panel, apposition of the TdTom and gephyrin signals. Scale bar of insets, 2 μm.

(B) Mean (±SEM) appositions per PKCγ neuron soma is not significantly different (Kruskal-Wallis test) in $tdTom^+$ alone (3.87 ± 0.41; white bar; n = 64 somata, six mice) compared to $tdTom^+$ colocalized with VAMP2 (3.31 ± 0.86; hatched bar; n = 10 somata, two mice) or $tdTom^+$ colocalized with GlyT2 (4.03 ± 0.64; gray bar; n = 13 somata, three mice) or $tdTom^+$ facing gephyrin clusters (2.51 ± 0.45; black bar; n = 10 somata, two mice).

(C) Electron micrographs of lamina IIi of the dorsal horn of a *PV::cre; tdTomato* mouse showing the association between PKCγ-IR dendrites (d; note silver-gold particles) and tdTom-IR boutons (note dense precipitate) indicated by arrows; note the presence a symmetric synapse (arrowheads) between the tdTom-IR boutons and the PKCγ-IR dendrites (d); b: unlabeled bouton.

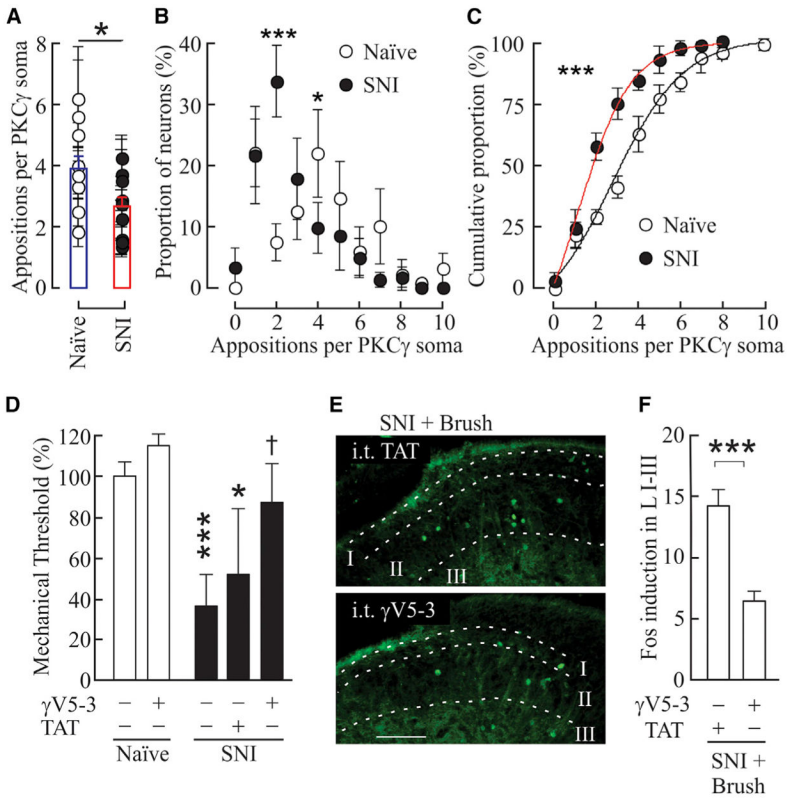


Figure 6. Nerve Injury Induces a Detachment of PV-PKCγ Appositions that Disinhibits PKCγ Interneurons

(A) The mean (±SEM) number of somatic appositions is significantly lower in nerve-injured (SNI) compared to naive mice (3.87 ± 0.41 in naive mice; n = 64 somata from six mice versus 2.63 ± 0.31 in nerve-injured mice; n = 54 somata from three mice; *p = 0,037; t test for unpaired data).

(B) Mean (±SEM) proportion (%) of PKCγ somata in relation to the number of PV appositions. (*p < 0.05, ***p < 0.001; test of independence in contingency table, Fisher's exact probability).

(C) Conversion of data in (B) into cumulative proportion demonstrates a leftward shift of the fit after nerve injury (SNI) (***p < 0.001, Kolmogorov and Smirnov test).

(D) Inhibition of PKCγ activity reduces mechanical allodynia produced after SNI. Naive mice were tested before (double minus) and 20–30 min after intrathecal (i.t.) injection of 100 pmol of γV5-3. The PKCγ inhibitor and its control (TAT peptide) were then tested on nerve-injured mice. *,***Significant difference compared to naive baseline (n = 8). †Significant effect of γV5-3 treatment compared to SNI baseline (n = 7), Wilcoxon signed-rank test for paired data.

(E) Representative images of brush-induced Fos expression in the dorsal horn of a nerve-injured mouse pretreated i.t. with TAT (upper panel) or γV5-3 (lower panel). Scale bar, 100 μm; roman numbers indicate lamina.

(F) Mean (±SEM) number of Fos-IR neurons per 25-μm section. In nerve-injured mice pretreated i.t. with TAT (n = 3), gentle brushing evoked Fos induction in neurons of laminae I–III ipsilateral to the nerve injury. In nerve-injured mice pretreated with γV5-3, brush-

evoked FOS induction is significantly lower (n = 3). ***Significant difference between the TAT and the γV5-3 groups. Mann-Whitney test.

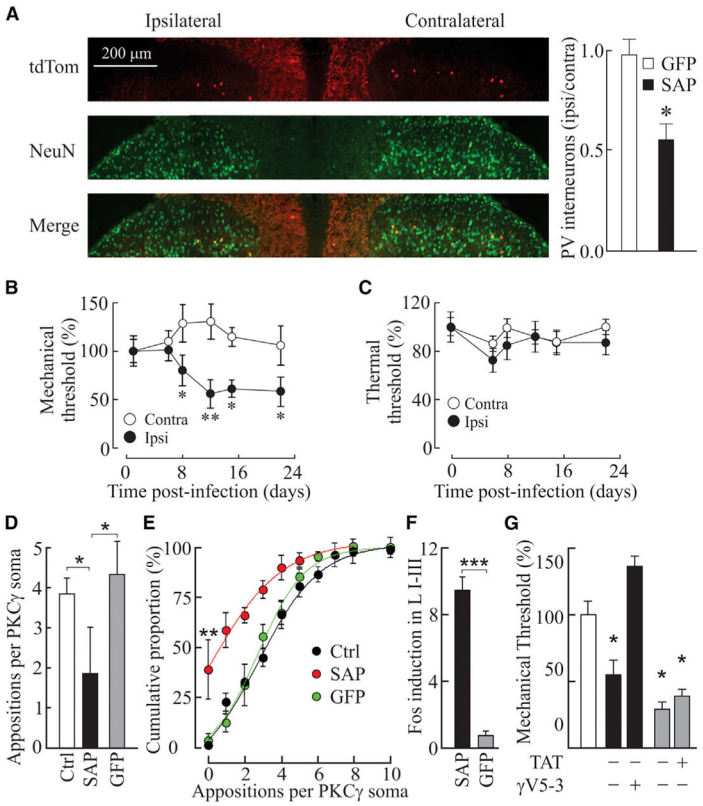


Figure 7. Saporin-Mediated Ablation of PV Neurons Induces a PKCγ-Dependent Mechanical Allodynia

(A) Composite image of a dorsal horn section of a PV::cre; tdTomato mouse injected with AAV-*Saporin* (SAP). There is a decrease in the number of tdTom$^+$ neurons on the ipsilateral side (top-left panel). No visible decrease in neuronal density is observed by neuronal staining (left, middle panel). Control mice were injected with a virus (same titer) expressing *GFP* (n = 4). The number of tdTom$^+$ neurons was counted on the ipsilateral and contralateral sides, and the ratio (±SEM) of ipsi/contra is plotted (right panel). *p < 0.05, Student's t test.

(B) Ablation of PV neurons triggers mechanical hypersensitivity ipsilateral (black circles) to the AAV-*Saporin* injection side. *Significant difference from contralateral side (white circles, n = 9).

(C) Ablation of PV neurons has no effect on paw withdrawal latencies in response to noxious thermal stimuli.

(D) The mean (±SEM) number of tdTom$^+$ processes apposing PKCγ somata is significantly lower in AAV-*Saporin*-injected mice (1.87 ± 1.18; n = 38 somata from five mice) than in control mice (3.87 ± 0.41; n = 64 somata from six mice) or in AAV-GFP-injected mice (4.36 ± 0.84; n = 30 somata from three mice). ANOVA (p = 0.013) with Tukey, all pairwise multiple comparison (*p < 0.05).

(E) The cumulative proportion of PKCγ in-terneurons with varying numbers of PV appositions is significantly shifted to the left in AAV-*Saporin*-injected mice (p = 4.23 E-5 VS. AAV-GFP-injected mice; Kolmogorov-Smirnov test). The proportion of PKCγ somata without tdTom$^+$ appositions is significantly higher in AAV-*Saporin*-injected mice (38.92% ± 14.6%; n = 38 somata; five mice) than in control mice (0%; n = 64 somata; six mice) or in

AAV-GFP-injected mice (6.36% ± 3.2%; n = 30 somata; three mice). **p < 0.01 AAV-*Saporin*- versus AAV-GFP-injected group. Test of independence in contingency table, Fisher's exact probability.

(F) Mean (±SEM) number of Fos-IR neurons in laminae I–III per 25-μm-thick spinal cord section. A gentle brushing of the hindpaw induces Fos expression ipsilateral to AAV-*Saporin* injection (9.44 ± 0.68 neurons; n = 6). It is not the case in AAV-GFP-injected mice (0.75 ± 0.25 neurons; n = 3). ***p < 0.001 AAV-*Saporin*-versus AAV-GFP-injected group, Mann-Whitney test.

(G) Mean (±SEM) mechanical withdrawal threshold, expressed as percentage of baseline (white bar). Mice were tested before and 30 min after i.t. injection of 100 pmol of either γV5-3 (n = 6) or the TAT peptide (n = 3). *p < 0.05; Friedman repeated-measures ANOVA on ranks with Tukey's post hoc test.